Influence of Nitrogen Rate and Form on Quality of Putting Greens Cohabited by Creeping Bentgrass and Annual Bluegrass

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ABSTRACT

Of the essential nutrients, N fertility generally influences golf course putting green (PG) quality and growth rate most significantly. Despite considerable field research on N fertility of PGs, results interpretation and transfer to practice is complicated by various influential factors; including unrepresentative mowing heights and/or frequency, varying irrigation water quality, undeclared composition of mixed swards, withdrawn cultivars, and/or use of temperature-dependent organic fertilizer sources. A 2-yr field study was initiated in 2003 at University Park, PA, to evaluate the influence of soluble N fertilizer source and rate on qualitative and nutritional parameters of a mature, primarily surface-drained, "push-up" PG cohabited by 'Penn A4' creeping bentgrass (*Agrostis palustris* Huds.) and annual bluegrass (*Poa annua* L.). Using an array of soluble N form quotients (NH_4–N/NO_3–N), split applications of annual N fertilizer rates ranging from 69 to 402 kg ha^{-1} were sprayed every 15 $\pm$ 4 d, April to October. Putting green growth, color, N uptake (NUP), and leaf N, K, Ca, Mn, Cu, and Zn increased directly with N rate, while plots receiving N rates in excess of 244 kg ha^{-1} yr^{-1} demonstrated acceptable PG quality and tissue nutrient concentrations. However, N rates >244 kg ha^{-1} yr^{-1} containing >50% NH_4–N significantly enhanced shoot growth, color, NUP, leaf Mn, P, and Mg levels, when compared to equal rates containing $\geq$50% NO_3–N. Frequent fertilization with NH_4–N at annual rates >244 kg ha^{-1} maximized canopy color and most tissue nutrient levels of a mature creeping bentgrass/annual bluegrass cohabited PG growing on a neutral, fine-textured soil.

Of all the managed turfgrass areas comprising a golf course, none are more valued or intensively maintained than the PGs. Putting green square footage may represent <2% of total managed golf course turf, yet cultural practices necessary to support its optimal performance consume disproportionately greater resources. Nitrogen fertility is an important component of putting green culture. Under optimal growing conditions and nutrient sufficiency, no other plant essential nutrient has as significant an influence on turfgrass canopy color and vigor (Waddington et al., 1978), root-to-shoot ratios (Schlossberg and Karnok, 2001), or disease susceptibility (Davis and Dernoeden, 2002). Likewise, when applied at rates commensurate with turfgrass requirements, traditional fertilizer sources providing any or all plant essential nutrient(s) besides N (except acids or liming agents) do not have as significant an effect on soil biochemical activity as N fertilizers.

Nitrogen fertilizers include numerous quick-release and slow-release forms, each having application-specific advantages. Use of quick-release fertilizers; defined as soluble, readily available nutrient sources, is appropriate for correcting deficiencies and/or use in light/frequent nutrient delivery programs. Likewise, greater, less-frequent applications can safely be made to turfgrass using slow-release fertilizers. When used properly, slow-release fertilizers steadily supply available nutrients and minimize risks of leaching and osmotic tissue desiccation (Carrow et al., 2001). However, because the more effective slow-release fertilizers are water-insoluble, coated, or both; they are only available in granular or sprayable-powder forms. This physical persistence of slow-release granular fertilizers requires them to either be watered through the canopy, stabilized in the upper soil profile (i.e., applied following aerification or verticutting procedures), or free to persist on the putting surface; reducing putting quality until being exported with clippings following daily mowing procedures. This is one of several justifications for applying liquid/spray fertilizers to PGs during periods of peak golfing activity. Further support of this application method is provided by recent evidence showing frequent/light fertilizer applications optimize plant health and nutrient recovery (Bowman, 2003). Moreover, potentially prohibitive additive costs associated with frequent fertilizer reapplication are negated by the common practice of weekly to semimonthly plant protectant and/or growth regulator applications to PGs already scheduled throughout the playing season.

Influence of N fertilizer form on nutrient assimilation by species of the *Gramineae* family is the subject of numerous research investigations; most being conducted in recently established hydroponic or disturbed soil systems, in controlled environments, and over short-duration experimental periods (Bailey, 1999; Picchioni and Quiroga-Garza, 1999; Bloom et al., 1992; Bowman and Paul, 1992; Bowman and Paul, 1988). Results of these studies have been mixed. Bailey (1999) showed greater uptake of ^{15}N in creeping bentgrass shoots, 3 and 15 d after fertilizing with primarily NH_4–N when compared with primarily NO_3–N. Likewise, hybrid bermudagrass [*Cynodon dactylon* (L.) Pers. × *C. transvaalensis* Burtt-Davey cv. Tifgreen] fertilized with $(NH_4)_2SO_4$ contained 9% more relative N in leaf clippings than bermudagrass fertilized with NH_4NO_3 (Picchioni and Quiroga-Garza, 1999). Bloom et al. (1992) and Bowman

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Abbreviations: CCRD, central composite rotatable design; DAT, days after treatment; DGCI, dark green color index; NUP, nitrogen uptake; PG, putting green; PSU-AASL, Penn State University Agricultural Analytical Services Laboratory.

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and Paul (1988) reported enhanced assimilation of reduced N by barley (*Hordeum vulgare* L.) and perennial ryegrass (*Lolium perenne* L.) respectively, when fertilized with NH_4–N sources compared to NO_3–N sources. Conversely, Bowman and Paul (1992) reported that fertilization by various N forms failed to influence perennial ryegrass leaf N recovery.

Two field studies have been conducted to quantify influence of N form on quality parameters of mature creeping bentgrass (cv. Penncross) (McCrimmon and Karnok, 1992; Mazur and Hughes, 1976); though the former was conducted in the 4- to 16-mo period following sod establishment. Both studies examined ratios of NH_4 and NO_3 fertilization, yet both implemented urea as the NH_4–N source. Mazur and Hughes (1976) did not observe any significant effects of N form on shoot quality, while McCrimmon and Karnok (1992) reported significantly greater shoot color in spring with 100% NH_4–N fertilized plots compared to plots treated with a 100% NO_3–N fertilizer. In the other three seasons, no color differences were observed between the 100% NH_4–N and NO_3–N treatments. However, plots fertilized with equal NH_4 and NO_3 forms showed significantly better shoot color than all other N form treatments.

Penn A-4 creeping bentgrass is categorized as a "high-density" bentgrass (Sweeney et al., 2001), and demonstrates particularly aggressive growth habit at mowing heights between 2.5 and 3.3 mm, as well as exceptional heat and wear tolerance (Landry and Schlossberg, 2001). In National Turfgrass Evaluation Program (NTEP) trials conducted nationwide, density and color ratings of Penn A-4 significantly exceeds most bentgrass entries, and resides in the highest statistical grouping for overall quality (NTEP, 2004; Voigt et al., 2006). Considering Penn A-4 is well adapted to several geographic regions and often coexists with annual bluegrass on golf course PGs; information that relates color, growth, and/or nutrient concentration of these mixed-sward greens by N fertilizer treatment will benefit golf course superintendents worldwide. Thus, the objectives of this study are to identify effects of frequent N fertilization rate and soluble N form on color, vigor, and nutrient concentration of golf course PGs cohabited by Penn A4 creeping bentgrass and annual bluegrass.

MATERIALS AND METHODS

This experiment was initiated in April 2003 on 280 m^2 of a mature, intensively managed PG cohabited by Penn A-4 creeping bentgrass and annual bluegrass. The soil profile comprises 7 cm of sand above a native Hagerstown silt loam (fine, mixed, semiactive, mesic Typic Hapludalfs). At experiment initiation, the putting surface was afflicted with varying levels of annual bluegrass contamination (5–30% of surface area). To minimize the impact of this spatially irregular nuisance variable, the experimental area was partitioned into three equally sized blocks that minimized the intrablock variability of annual bluegrass occupancy (Karcher et al., 2003). Maintenance applications of fertilizers were applied to the green in 2002, yet N fertilizers were purposely withheld after 18 August. In March 2003, the 2- to 9-cm soil depth of the PG root zone was thoroughly sampled and multiple composites (thatch removed) submitted to the Penn State University Agricultural Analytical Services Laboratory (PSU-AASL, University Park, PA) for routine analysis (Table 1).

Table 1. Physicochemical properties of PG soil sampled from 2- to 9-cm depth (thatch removed), at experiment initiation (March 2003).

Property	Value
Soil pH_W (1:1)	7.0 ± 0.1†
Soil OM‡, g kg^{-1}	40 ± 1
CCE_{Sand}§, g kg^{-1}	20 ± 1
Mehlich 3 extractable	
K, $mmol_c$ kg^{-1}	1.8 ± 0.2
Mg, $mmol_c$ kg^{-1}	15.0 ± 0.5
Ca, $mmol_c$ kg^{-1}	62.8 ± 2.0
CEC¶, $mmol_c$ kg^{-1}	81.4 ± 3.6
P, mg kg^{-1}	64 ± 2

† Standard error (SE) of the mean value.
‡ Soil organic matter, by loss on ignition (LOI).
§ CCE, calcium carbonate equivalency of mineral fraction retained in a 250-μm sieve.
¶ CEC, cation exchange capacity by summation of exchangeable base cations and Mehlich buffer pH exchangeable acidity.

Beginning late April 2003, N fertilizer treatments were applied to the experimental plots (92 by 183 cm). The initial fertilizer application comprised one-fifth of the corresponding annual rate, with successive applications of approximately one-fifteenth of the annual rate made on 15- ± 4-d intervals (Fig. 1). Nitrogen rate (kg ha^{-1} yr^{-1}) and N form [expressed as the quotient of ammonium-nitrogen mass (g NH_4–N) to nitrate-nitrogen mass (g NO_3–N)] comprised the two continuous variables of a second-order factorial arrangement in a central composite rotatable design (CCRD) (Box and Hunter, 1957; Draper, 1982). Annual N fertilizer application rate ranged from 69.1 to 402.4 kg ha^{-1} [1.41–8.25 lb. $(1000\ ft^2)^{-1}$], while NH_4–N/NO_3–N quotients ranged from 26 to 1/26 (Table 2). Technical-grade NH_4NO_3 was used as the sole source of the lesser component, with either calcium nitrate, $Ca(NO_3)_2{\cdot}4H_2O$ (New Eezy-Gro, Carey, OH), or ammonium sulfate, $(NH_4)_2SO_4$ (Honeywell Specialty Materials Division, Morristown, NJ), used to fulfill the respective NO_3– or NH_4–N remainder.

All fertilizer applications were delivered by a CO_2–powered, single nozzle (Tee-Jet TP11008E, Spraying Systems

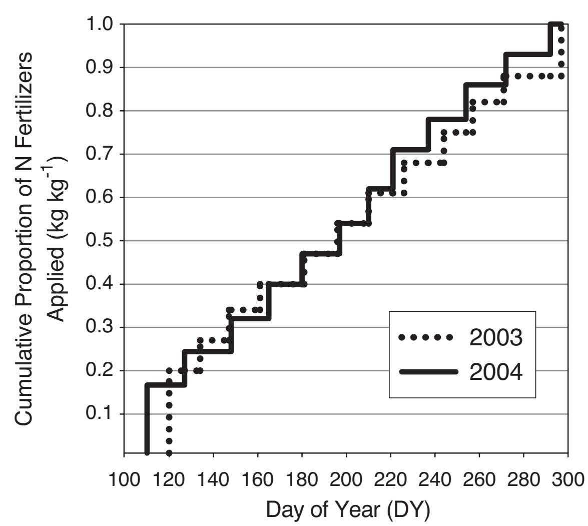

Fig. 1. Cumulative representation of N fertilizer applications by day of year (DY).

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Table 2. Experiment factors and codes of the central composite rotatable design (CCRD).

Field formulations and rates		Experimental codes		Replicates per block
N form	N rate	x_1 (N form)	x_2 (N rate)	
g NH_4–N/g NO_3–N	kg ha^{-1} yr^{-1}	log (N form)	(N rate − a) (b − 1)†	
0.10	117.9	−1	−1	1
10.00	117.9	1	−1	1
0.10	353.6	−1	1	1
10.00	353.6	1	1	1
0.04	235.7	−1.414	0	1
25.94	235.7	1.414	0	1
1.00	69.1	0	−1.414	1
1.00	402.4	0	1.414	1
1.00	235.7	0	0	5

† a = mean of −1 and 1 rates; b = half the difference between −1 and 1 rates.

Co., Wheaton, IL), wand sprayer at a rate of 995 L ha^{-1} H_2O at 207 kPa. Due to salt indices of the fertilizers, application volume of the treatments, and/or increasing temperatures; osmotic and/or phytotoxic injury began appearing on plots (1 July) after applications of N treatments >235.7 kg ha^{-1} yr^{-1} [>0.32 lbs (1000 ft^2 application)$^{-1}$]. Thus, the following preventative measures were employed thereafter: applications were postponed until 1600 h, the high N rate treatments were applied last, and ~1 cm of potable irrigation water was applied to the PG once all treatments had been applied. As a result, visual injury was prevented outright or minimized before desiccated tissue was removed by mowing the next day. Digital imagery data, later used to measure canopy color, were not collected before the described adjustments were made.

Management procedures conducted onsite were similar to standard golf course practice. Potable irrigation water was applied to prevent wilt, and plant protectants were used to control pests when necessary. No herbicides, surfactants, growth regulators, or systemic fungicides were applied over the 2-yr study. The green was mowed at a height of 3.1 ± 0.1 mm, six to seven times weekly, April through October. Plots were not mowed the day before collecting clipping yields. Clipping yields were collected 6 to 14 d after treatment (DAT) on: 24 July, 8, 20, and 28 Aug. 2003. Once dried and weighed, clipping samples (from each yield date and experimental unit) were ground to pass a 0.15-mm sieve and randomly split. A 0.4-g subsample was submitted to the PSU-AASL for dry ash determination of leaf P, K, Ca, Mg, Fe, Mn, Cu, and Zn concentration (Miller, 1998), while two independent 0.15-g subsamples were analyzed for total leaf N by medium temperature furnace combustion (Sweeney and Rexroad, 1987). Nitrogen uptake (NUP) was calculated as the product of oven-dry clipping yield (kg ha^{-1} d^{-1}) and leaf tissue N (g kg^{-1}) on a per plot basis and analyzed as a dependent variable.

High-resolution JPEG-formatted images (2560 by 1920 pixels, 8.9-mm focal length, various shutter speeds and apertures) were collected using a hand-held digital camera (Nikon E5700, Nikon Corp., Melville, NY) on 28 July, 19 Aug., 10 and 28 Sept., and 10 Oct. 2003. Plot image capture was conducted only during cloudless periods, at identical orientation to the sun, and successively by experimental block. Average red, green, and blue levels of each image were determined using SigmaScan Pro software (Version 5.0, SPSS, Chicago). These average levels were converted to hue, saturation, and brightness values to calculate dark green color indices (DGCI) by the method of Karcher and Richardson (2003). Two rounds of image capture were conducted on most dates and averaged as subsamples before statistical analysis.

Following the last N treatment applications (24 Oct. 2003), maintenance fertilizer applications were applied across all plots using granular muriate of potash (0–0–60, 58 kg ha^{-1} K) and triple super phosphate (0–46–0, 39 kg ha^{-1} P). One week later, a topdressing of sand and synthetic gypsum ($CaSO_4 \cdot 2H_2O$, Southern Company, Birmingham, AL) was broadcast applied equally across all plots at rates of 60 m^3 ha^{-1} and 290 kg ha^{-1}, respectively. The experimental PG was not mowed again for the remainder of the 2003 season.

General PG maintenance practices resumed early April 2004. Identical annual N rates/forms (Table 2) were implemented in the 2004 season, yet the following changes were made: (i) fertilizer carrier volume was reduced to 888 L ha^{-1} H_2O, (ii) initial treatments were applied at one-sixth the annual rate on 20 April, and (iii) treatments of approximately one-thirteenth the annual rate were applied semimonthly thereafter (Fig. 1). Clipping yields were collected (8–13 DAT) as described above on 27 June, 8 July, and 6 Aug. 2004. Digital images were collected on 3 and 10 June, 3 and 29 Aug., and 3 and 14 Oct. 2004. Otherwise, all 2004 data collections and analyses followed the above-described methods for 2003.

Coded treatment levels (Table 2) and associated data were entered into the response surface regression (PROC RSREG) and/or linear regression (PROC REG) subroutine(s) of SAS/STAT (SAS Institute, 1998, Version 8.2). Models predicting nutrient concentration, DGCI, clipping yield, or NUP were iteratively tested with (and without) block and/or year covariates. Only response surfaces predicted by significant models ($P \leq 0.01$) meeting the following criteria are displayed in their second-order form: (i) insignificant lack-of-fit test [$P(F_0) >$ 0.05] (Draper and Smith, 1983); and (ii) both N rate and N form type III mean squares were significant ($P \leq 0.10$). In cases where multiple models met the above criteria, the one with the lowest CV value is shown.

RESULTS AND DISCUSSION

Penn A-4 creeping bentgrass/annual bluegrass cohabited PG growth significantly responded to N fertilization rates and forms (Table 3). The range of shoot growth/clipping yield observed (17.2–50.6 kg ha^{-1} d^{-1}) is in

Table 3. ANOVA of N uptake (NUP), PG qualities, and nutrient concentrations by N treatments.

			PG quality and leaf tissue nutritional status parameters										
					Leaf tissue nutrient concentration								
Source	df	N uptake (NUP)	Clipping yield	Dark green color index	N	P	K	Ca	Mg	Mn	Cu	Zn	Fe
N rate	3	***	**	**	***	†	†	**	†	***	***	***	NS
N form	3	**	***	†	NS	†	†	NS	***	***	***	*	NS
Covariates	0–2	yr, blk	yr	yr	yr	yr, blk	yr, blk	–	–	yr	yr	–	–

* F values significant at the 0.05 alpha level.
** F values significant at the 0.01 alpha level.
*** F values significant at the 0.001 alpha level.
† F values significant at the 0.1 alpha level.

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agreement with recent PG field data (St. John et al., 2003). When N was applied as mostly NH_4, clipping yield increased linearly from <18.3 to 50.6 kg ha^{-1} d^{-1} over respective annual N rates of 98 to 391 kg ha^{-1} (Fig. 2a). A linear increase in clipping yield was also observed with NO_3–N (0.039 NH_4–N/NO_3–N quotient), but only increasing from 24.8 to 39.8 kg ha^{-1} d^{-1} as N rate increased from 98 to 391 kg ha^{-1} yr^{-1}. Annual N rates <147 kg ha^{-1} containing primarily NH_4–N forms resulted in ~23% less biomass production than low N rates containing primarily NO_3–N forms. Daily biomass production rates under moderate N fertilization (146–244 kg ha^{-1} yr^{-1}) varied little by N form. However, higher N rates (>244 kg ha^{-1} yr^{-1}) comprised of primarily NH_4–N showed 14 to 25% greater biomass production than NO_3–N fertilized plots (Fig. 2a). This increase in biomass in the high N rate (>244 kg ha^{-1}) portion of the response surface is attributed to the NH_4–N form; however, there is a potentially confounding factor of the fertilizer formulations to be noted. For the two greatest NH_4–N/NO_3–N quotients (26 and 10), the primary N source [$(NH_4)_2SO_4$] included S. Thus, these treatments provided concomitant plant available S in proportion to increasing NH_4 concentration. Enhanced shoot growth could be attributable to additional S, but seems unlikely in this case because high rates of ferrous sulfate were frequently applied to the plots throughout the fall of 2002 (15 kg $FeSO_4$ ha^{-1} providing 2 kg ha^{-1} S), and 55 kg ha^{-1} S was applied as synthetic gypsum in fall 2003.

The dark green color index (DGCI) is a primary indicator of aesthetic quality of turf (Karcher and Richardson, 2003), and DGCI of the cohabited PG was significantly affected by N rate and form (Table 3). When the N fertilizer source was predominantly NH_4, DGCI increased from 0.41 to 0.46 respective to the 98 to 391 kg ha^{-1} yr^{-1} N rates. In contrast, when the primary source of N was NO_3, DGCI showed little response to N rate (Fig. 2b). Canopy DGCI for the 0.039 NH_4–N/NO_3–N plots at the 391 kg N rate was 98% of the grand mean for this N form (DGCI = 0.426), and only 101% of that mean at its maximum DGCI value of 0.43 (195 kg ha^{-1} yr^{-1} N rate). Interestingly, canopy color of lower N rate plots [98–146 kg (ha yr)$^{-1}$] was greatest at the 1 and 0.1 NH_4–N/NO_3–N forms. On the contrary, when annual N fertilization rate exceeded 150 kg ha^{-1}, canopy dark green color was maximized with foliar fertilizers that contained a majority of NH_4–N. These results again raise the question of concomitant sulfate influence on the NH_4 side of the response surface. However, the data show a comparatively smooth response from the 1 NH_4–N/NO_3–N quotient to the 10 and 26 NH_4–N/NO_3–N quotients at all N rates, and none of the 1 NH_4–N/NO_3–N fertilizer formulation contained S (Fig. 2b). Improved turf color with increasing NH_4 content of N fertilization rates >195 kg ha^{-1} yr^{-1}, is in agreement with other observations (Glinski et al., 1990).

Reports of improved shoot color (Glinski et al., 1990), shoot growth (Picchioni and Quiroga-Garza, 1999), and/or NUP (Bailey, 1999; Bloom et al., 1992; Bowman and Paul, 1988) by NH_4–N fertilization have addressed whole plant responses. Whole-plant studies that directly measured greater NH_4 uptake from NH_4–N fertilization than NO_3 uptake from NO_3–N fertilization report either increased (Bailey, 1999; Bloom et al., 1992), indiscernible (Picchioni and Quiroga-Garza, 1999), or decreased root growth response. Bowman and Paul (1988) measured 8% greater perennial ryegrass root mass accumulation with NO_3–N treatment than by NH_4–N treatment during the 48-h period immediately following N application. However, the NO_3 fertilized plants were preferentially treated with incremental solution NO_3 increases over a 6-h ramping stage, before study initiation. Furthermore, NO_3 absorption over the subsequent 48-h period was significantly (25%) less than NH_4 root absorption, and assimilation yield of the NH_4 fertilized turfgrass was twice as great (Bowman and Paul, 1988).

In studies where direct measures of NH_4 uptake were not made, comparisons of root growth by N form varied widely by soil depth and season (McCrimmon and Karnok, 1992). Reports of significantly reduced root growth of creeping bentgrass (Glinski et al., 1990) or creeping bentgrass/annual bluegrass polystands (Eggens and Wright, 1985) from NH_4 (compared with primarily NO_3) fertilization have been generated from short-term greenhouse studies. Glinski et al. (1990) concluded that root mass of bentgrass fertilized solely by NH_4–N was significantly less than plants fertilized with 75 to 100% NO_3–N. However, these results may be confounded by nitrification-induced Al toxicity. Over the 37-d study, eight repeated applications (15.6 kg N ha^{-1}) comprised of 100 or 75% NH_4–N drove the pH of the poorly buffered root zone from an initial pH of 5.4 to 4.1 or 4.2, respectively. Considering the pK_a of Al is approximately 4.9, bentgrass rooting would be severely restricted at the observed soil pH levels. Likewise, the validity of similar results presented by Eggens and Wright (1985) must be weighed against the extraordinary 637 kg ha^{-1} N rate applied over the 55-d studies, the associated potential for NO_3 leaching through a sand root zone (compared to NH_4) during irrigation-intensive establishment periods, the absence of supporting N recovery data, and the adverse effects of supraoptimal N fertility on root growth of intensively managed cool season turfgrasses (Schlossberg and Karnok, 2001).

The greater clipping yield and DGCI responses to NH_4–N sources compared to NO_3–N sources observed in our field study may be a consequence of the lesser energy requirement for physiological assimilation of NH_4–N. Plant cells expend 20 adenosine triphosphate (ATP) reducing and assimilating a NO_3 anion, but assimilation of an NH_4 cation expends only 5 ATP (Salsac et al., 1987). Under intensive management typical of PG culture, the greater comparative cost of NO_3 assimilation may have reduced energy reserves that would have otherwise supported protein synthesis and/or cell division (shoot growth). Likewise, because NH_4 is readily coupled in cytoplasm by glutamine synthetase, NH_4 transport from soil solution to symplast is passive and driven by concentration gradient (Givan, 1979). On the contrary, active transport of NO_3 anions into cytoplasm

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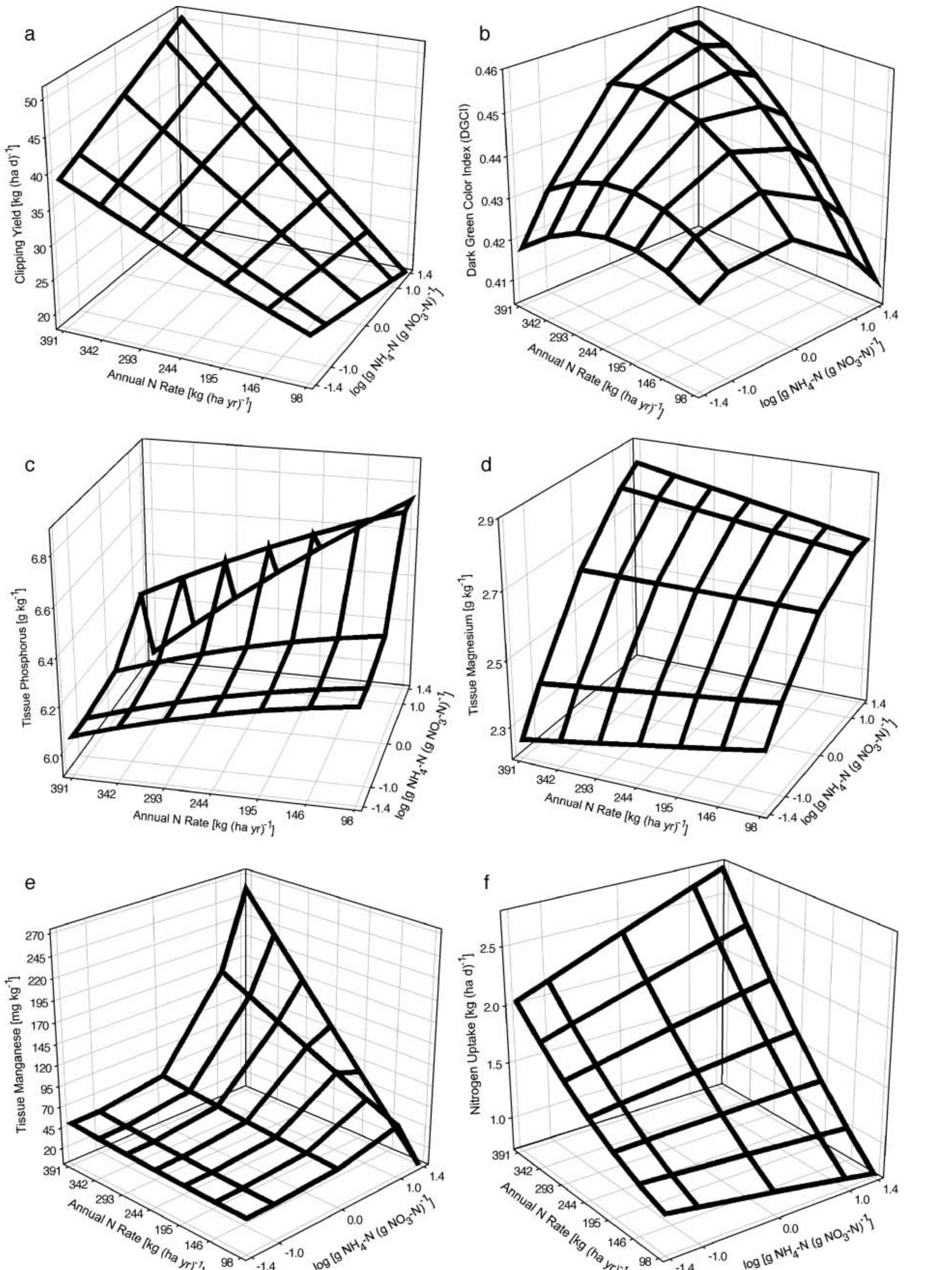

Fig. 2. (a) Clipping yield, (b) dark green color index, (c) leaf P, (d) leaf Mg, (e) leaf Mn, and (f) N uptake of a Penn A4 creeping bentgrass/annual bluegrass cohabited PG by N fertilization rate and form.

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requires 9 to 10 kJ mol^{-1} (Salsac et al., 1987). One or both of these mechanisms may have contributed to the greater clipping yield and DGCI observed in the NH_4–N fertilized plots.

Tissue P was significantly affected ($P < 0.1$) by interacting N fertilization rates and forms (Table 3, Fig. 2c). Leaf P concentration ranged from 5.9 to 6.8 g kg^{-1}, well above the general turfgrass sufficiency range of 2.2 to 5.5 g kg^{-1} suggested by Carrow et al. (2001). However, increasing N rates resulted in decreasing leaf P concentration, regardless of the N form applied (Fig. 2c). When NO_3 was the dominant form of N fertilizer, leaf P concentration decreased from 6.3 to 6.1 g kg^{-1} as N rate increased from 98 to 391 kg ha^{-1} yr^{-1}. A decreasing trend in leaf P concentration was also observed when N fertilizer was applied as NH_4, decreasing from 6.7 to 6.0 g kg^{-1} P across the same N rates. While leaf P concentration was enhanced when NH_4 was the dominant N form applied (10 and 26 NH_4–N/NO_3–N quotients), leaf P for the 10 NH_4–N/NO_3–N quotient exceeded levels observed of the 26 NH_4–N/NO_3–N quotient (Fig. 2c).

Decreasing leaf P concentration with increasing N rate (all forms) may be a consequence of the direct clipping yield response to N rate (Fig. 2a). Rehm et al. (1977) reported decreasing leaf P concentrations with increasing N fertilizer rates in mixed pastures containing Kentucky bluegrass (*Poa pratensis* L.), and implicated the dilution effect of rapid tissue growth. Likewise, regression analysis shows a significant indirect relationship of leaf P to shoot biomass production rate in our study (Fig. 3). Leaf dark green color increased with N rate whereas leaf P concentration decreased (Fig. 2b and 2c), thus leaf P levels as low as 6.0 g kg^{-1} had no deleterious effect on growth rate or canopy dark green color. These data are in agreement with the leaf P deficiency threshold of creeping bentgrass (4 g kg^{-1}) suggested by Guillard and Dest (2003).

Interacting effects of N form and rate influenced leaf Mg concentration over the course of the field study. Increasing NH_4–N fertilizer content significantly increased leaf Mg by 12% at the 98 kg N rate to 25% greater leaf Mg for the 391 kg rate (Fig. 2d). Magnesium sufficiency has been reported to positively influence leaf chlorophyll concentration in several grass species (Marschner, 2002). These leaf Mg concentrations (Fig. 2d) reside within the optimal range for cool season turfgrass species (Mills and Jones, 1996).

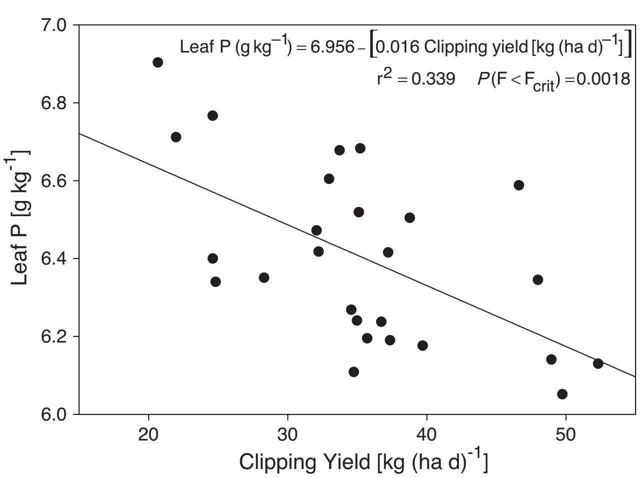

Fig. 3. Regression model for prediction of leaf P by cohabited PG daily clipping yield (shoot growth). Each symbol represents the mean of 12 or 9 data collections [3 block replicates by 4 (2003), or 3 (2004) repeated measures].

The plant-essential micronutrient concentration in PG leaves most significantly affected by N fertilizer rate and form was Mn. When NO_3–N comprised >90% of fertilizer N, mean leaf Mn increased from 42 to 51 mg kg^{-1} over annual N rates of 98 to 391 kg ha^{-1}, respectively (Fig. 2e). Conversely, mean leaf Mn increased from 31 to 211 mg kg^{-1} over the same range of annual N rates when NH_4–N comprised >90% of fertilizer N (Fig. 2e). A recent study showed creeping bentgrass to maintain a mean Mn tissue level of 67 mg kg^{-1} (ranging from 51 to 80 mg Mn) when growing on sandy soil with a pH level between 6.1 and 6.9 (Heckman et al., 2003). In that same study, bentgrass plots fertilized foliarly with $MnSO_4$ generated clippings with leaf Mn concentrations of 84 mg kg^{-1} (ranging from 47 to 257 mg Mn). The observed range of leaf Mn in our study (Fig. 2e) is very similar to the above results, yet no Mn fertilizers were applied over the 2-yr trial. Creeping bentgrass resistance to take-all patch disease, caused by *Gaeumannomyces graminis* (Sacc.) Arx. & D. Oliver var. *avenae* (E.M. Turner) Dennis, has been positively correlated to foliar Mn fertilization (Heckman et al., 2003). However, due to the immobility of assimilated Mn within the plant, maintenance of optimal tissue Mn levels by foliar fertilization proves difficult under typical golf course mowing/clipping removal regiments. Considering both the well-documented soil acidification effect of NH_4 fertilizers and the propensity of Mn to oxidize into plant unavailable forms with slight increases in alkalinity (Foth and Ellis, 1997), NH_4 fertilizer-induced rhizosphere acidification likely fostered Mn availability that resulted in greater leaf Mn concentration in the cohabited PG (Fig. 2e), whereas repeated foliar applications of $MnSO_4$ have not been proven as effective (Heckman et al., 2003).

Leaf N concentration increased from 42.1 to 51.2 g kg^{-1} with increasing N rate (Fig. 4). These tissue N levels are generally considered sufficient for both creeping bentgrass and annual bluegrass turfgrasses maintained as PGs. Nitrogen uptake was analyzed as a dependent variable and was affected by both N rate and form (Table 3). The NUP response surface (Fig. 2f) is essentially the predictive response of per-plot multiplications of data used to construct Fig. 2a and 4; and demonstrates the additive increase in NUP with increasing growth of shoots (Fig. 2a) having greater leaf N concentrations (Fig. 4). Considering leaf N concentration was unaffected by N form (Table 3), leaching of NO_3 (or reduced recovery) is not likely to have been responsible for these observed differences in NUP (Fig. 2f).

Unlike leaf P, leaf K concentration increased directly with N fertilization rates, regardless of N form (Fig. 4). However, this significant variation in leaf K by N fer-

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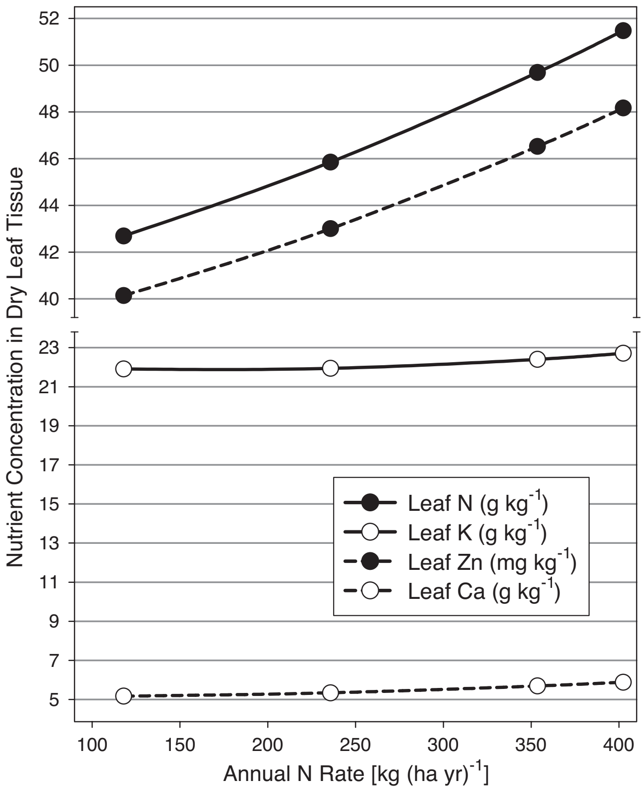

Fig. 4. Leaf N, Zn, K, and Ca concentrations of a Penn A4 creeping bentgrass/annual bluegrass cohabited PG by N fertilization rate.

tilizer rate and/or form only resulted in a ±5% relative swing around a mean of 22.3 g kg^{-1}. This mean tissue K level resides within the K sufficiency range of creeping bentgrass suggested by Mills and Jones (1996), and mirrors creeping bentgrass K levels of clippings collected from field plots receiving annual 76 kg ha^{-1} K fertilizer treatments (Waddington et al., 1978). Regardless of N treatment levels, a significant linear relationship between tissue N and K levels was observed (Fig. 5). Recent study of calcareous creeping bentgrass PGs report tissue K to correlate to tissue N with equal or greater dependability than to extractable soil K levels (Woods et al., 2006; Johnson et al., 2003); implicating mass flow/convection as the primary soil K uptake mechanism of cool season turfgrass root systems.

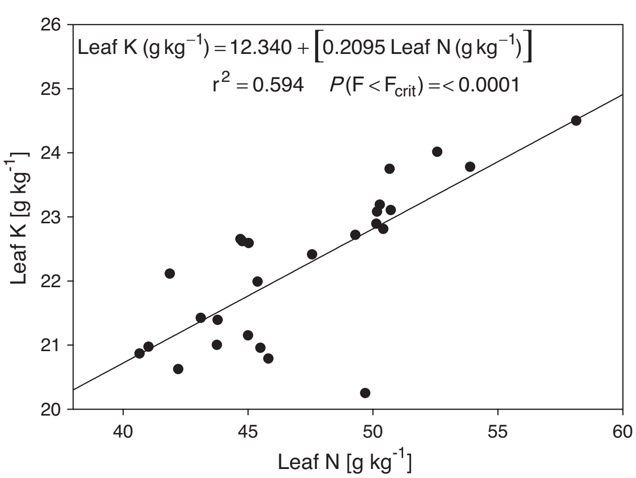

Fig. 5. Regression model for prediction of leaf K by cohabited PG leaf N. Each symbol represents the mean of 12 or 9 data collections [3 block replicates by 4 (2003), or 3 (2004) repeated measures].

Calcium in leaf tissue collected from the bentgrass/annual bluegrass cohabited green was affected solely by N fertilizer rate, while tissue Fe concentration (ranging from 132 to 224 mg kg^{-1}) was unaffected by N fertilizer treatments (Table 3). Tissue Ca related directly to N fertilization, increasing from 5.2 to 5.8 g Ca kg^{-1} over the 98 to 391 kg ha^{-1} annual rates (Fig. 4). Both leaf Zn (Fig. 4) and Cu (data not shown) were significantly affected by N fertilizer rate and form (Table 3), yet with limited agronomic consequence. Both micronutrients accumulated at concentrations well within their established sufficiency range (Carrow et al., 2001), and in direct relation to N fertilization rate.

CONCLUSIONS

Increasing N rate via frequent fertilization significantly increased clipping yield, canopy color (DGCI), leaf N, and leaf micronutrient concentrations, especially when the N fertilizer was comprised of NH_4. Increased clipping yield is often an undesirable effect of increased N fertility on golf course PGs, as decreasing ball roll distance is a function of shoot growth in the 12- to 24-h interval between mowing procedures. Results indicate N form had little influence on the moderate levels of clipping yield at the 170 to 270 kg ha^{-1} annual rates, yet DGCI values increased in this range of N rates with increasing NH_4–N/NO_3–N quotients (Fig. 2b). On the contrary, fertilization with sources containing greater NO_3–N than NH_4–N increased yield and DGCI at annual rates <170 kg ha^{-1}. At annual rates >270 kg ha^{-1}, DGCI values increased relative to the NH_4–N/NO_3–N quotient in fertilizer, yet concomitant clipping yield increases occurred. Compared to primarily NO_3–N sources, application of soluble fertilizers having NH_4–N/NO_3–N quotients exceeding one generally maximized plant uptake of macronutrients (P, K, Mg) in a neutral soil possessing optimum nutrient levels for maintenance of PGs (Table 1). On these bases, inclusion of water-soluble NH_4–N sources in frequent fertilizer applications to PGs having near-neutral soil pH levels appears advantageous, when compared to use of primarily NO_3–N sources. Response of cohabited PG DGCI, yield, and leaf nutrient concentration to N form by rate interactions justifies further experimentation, ideally over a wider array of climatic and edaphic conditions.

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